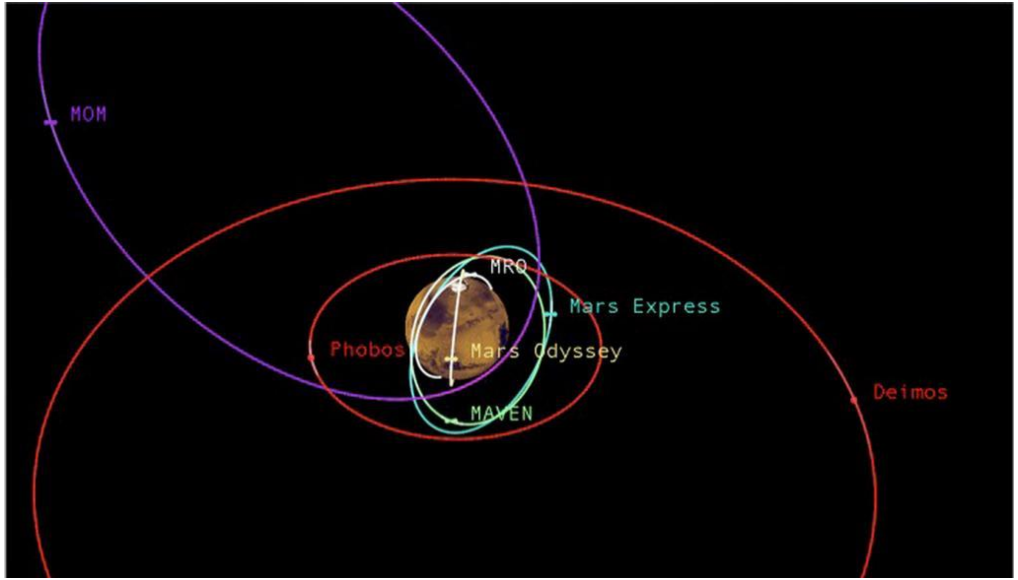


# Automated Spacecraft Conjunction Assessment at Mars and the Moon - A Five Year Update

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# Introduction

- Earth has a well known, ongoing problem with space debris in both LEO and GEO
- Some Earth orbiting missions have several close approaches with debris each month
- Earth's orbital environment is continuously surveyed by the US Space Surveillance Network (SSN), tracking objects down to approximately 10 cm in radar cross section
- At Mars and the Moon, the growing number of orbiter missions makes debris management one of avoiding the creation of a hazardous debris field in the first place
  - An orbital debris environment does not honor national boundaries
- NASA currently assesses satellite conjunctions in environments with multiple orbiters
  - Earth: Conjunction Assessment Risk Analysis (CARA) at NASA/GSFC
  - Mars: Starting in 2004, manual assessments by NASA/JPL
  - Mars/Moon: Since 2011, automated assessments conducted by JPL using Multimission Automated Deepspace Conjunction Assessment Process (MADCAP)
- A paper introducing JPL's work and state of automated operations was presented at Space Ops in Stockholm, Sweden in 2012, along with items identified for future work

# Overview

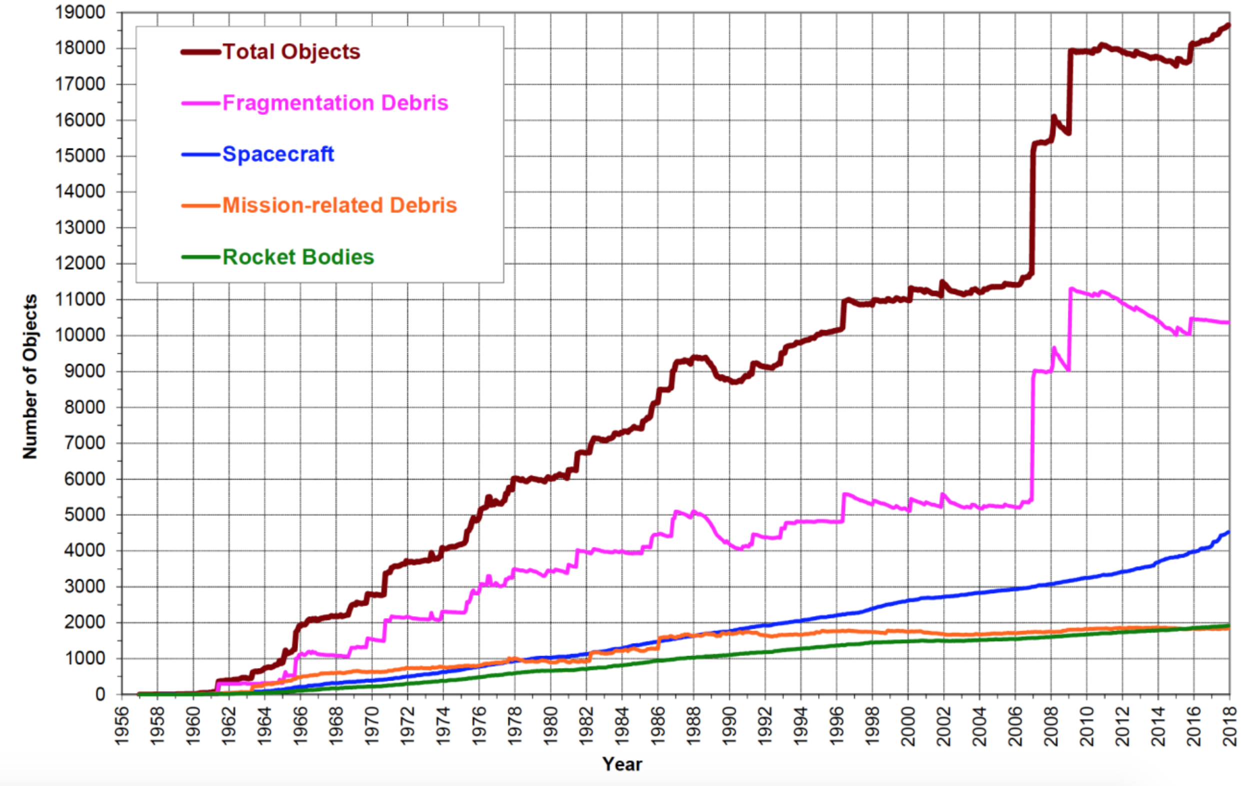
- This presentation will describe:
  - An update to the 2012 paper that identifies which future work items have been completed in the past five years
  - ... which work items have not yet been completed
  - ... and the current status of the overall effort
  - As in the 2012 paper, we conclude by identifying a few items for potential future work and the current state of planning for some of these

# The Orbital Debris Problem

- NASA Orbital Debris Program Office cites ~18,500 objects officially cataloged by SSN
- >50% are "fragmentation debris" (includes satellite breakup & anomalous event debris)
- Worst Earth orbiter breakups in history: intentional destruction of Fengyun-1C (FY-1C) in January 2007, collision between Cosmos 2251/Iridium 33 February 2009
  - A total of 5579 fragments were cataloged by the US SSN for these two events
  - As of April 2018 > 4200 still in orbit: Fengyun = 2833, Cosmos = 1076, Iridium = 335
- Models predict hundreds of thousands of untrackable < 10 cm fragments also created
- Even small particle impacts can cause spacecraft damage, generate more debris
- Currently no known orbital debris field at Moon or Mars, undesirable to create one as it would complicate existing/future operations, and could take many years to dissipate
- No way to realistically track debris from Earth as is done with SSN
- Growing number of orbiter missions at Mars/Moon and current inability to track orbital debris there suggest a focus on avoiding the creation of a debris field in the first place
- The necessity of this debris prevention function provided the inspiration for MADCAP

# Figure 1: Number of SSN Cataloged Objects in Earth Orbit

## By Object Type



# MADCAP Fundamental Design Concepts

- Fundamental design concepts of MADCAP have not materially changed since 2011
- Parameter file for each orbital environment to be analyzed, no change to software
- Key parameter classes: environment (central body, coordinate system); bodies in orbit (active & inactive spacecraft, natural bodies); thresholds to classify conjunction events
- Automatically initiated, MADCAP automatically downloads latest ephemerides from Deep Space Network's (DSN) Service Preparation Subsystem (SPS) portal
- Supplementary ephemerides for planned and/or non-operational missions, missions not using the DSN/SPS, and natural bodies not available on SPS can be added
- MADCAP then performs pairwise close approach event searches using the collection of ephemerides; each relative minimum distance is called a "close approach event"
- Candidate close approach events are evaluated against mission-established, risk-based thresholds prepared by navigation teams to classify them as "red" or "not red"
- "Red Event": a close approach event 14 days or less in the future for which the selected orbital attribute is below the defined threshold values
- Three types of reports are prepared and communicated by email to interested parties

# CA at Mars and the Moon Circa 2012

- JPL's automated spacecraft conjunction assessment at Mars and Moon was presented at Space Ops 2012 in Stockholm, Sweden after one year of MADCAP operations
- Fundamental MADCAP concepts designed/implemented, improvement ideas existed
- Primary attribute for conjunction assessment was "close approach distance" (CAD)
- MADCAP Summary Report focused on CAD; categorized close approaches as green, yellow, or red depending on magnitude of close approach and nav team thresholds
- MADCAP could only use "constant covariance"; no means to incorporate a covariance into the SPICE/SPK (Spacecraft Planetary Kernel) ephemeris files used by DSN/SPS
- In Stockholm paper, items identified for future work included:
  - Formalize a process for responding when approaches are "too close"
  - Refine uncertainty modeling to improve collision probability calculation
  - Collaboration with NASA/GSFC & ESA's Space Situational Awareness program
  - Incorporate more sophisticated automation than Linux "cron"
  - Include other shared orbital environments of potential interest
  - Provide an option to output a CCSDS Conjunction Data Message (CDM)

# MADCAP - Planned Changes Since 2012

## Responding to "Too Close" Situations

- In 2012 formal response to approaches that were "too close" was not documented
- At the time it was acknowledged that a formal process would be desirable
- In 2014, formal process for responding to spacecraft approaches that are "too close" was developed by JPL's MDNav Section and the Mars Program Office at JPL
  - Around the time NASA's MAVEN and ISRO's Mars Orbiter Mission entered orbit
- "Conjunction Assessment Process For Mars Orbiters" discusses requirements, has flowcharts for "Monitor Process" and "Response Process", specifies report recipients
- Monitor Process is realized in MADCAP Summary Report emailed at end of each run
- Report provides overall assessment of environment, identifies red and  "not red" events
- Response Process is triggered when a red event is reported in a Summary Report
- "MDNAV MADCAP Representative" contacts Nav Team Chiefs for spacecraft involved, discusses options, works out a time table for actions, provides status to key personnel
- In many cases the red events disappear "naturally" as the time to the event decreases, however, in some cases it has been necessary for at least one spacecraft to maneuver

# MADCAP - Planned Changes Since 2012

## What is "Too Close"?

- Operational definitions of "too close" have been significantly refined since 2012
- This has primarily involved refinements of trajectory uncertainty modeling
- MAVEN's arrival at Mars in September 2014, and the atmospheric drag of its science orbit on each periapsis pass, caused change of conjunction metric from absolute close approach distance to orbit crossing distance (OXD) and orbit crossing timing (OXT)
- Helps reduce problem of "false" red events which would not present any collision risk
- Changes in late 2014 also included move away from fixed constant thresholds towards dynamic time-to-event quadratic polynomial-based or covariance-based thresholds
- Process was simplified to "red" and "not red" conjunctions (instead of green/yellow/red)
- Red Event:  OXD and OXT less than mission thresholds, <= 14 days in the future
- It is "not red" if greater than 14 days in the future
- In summer 2015, a method of utilizing covariance data provided by nav team was added to MADCAP by using covariance matrix feature available in CCSDS OEM V2
- If covariance data is in ephemeris it will be used to calculate the conjunction thresholds

# MADCAP - Planned Changes Since 2012

## Working With NASA CARA and ESA

- JPL has been working on an informal basis with NASA's CARA program
    - Division of labor: CARA monitors Earth environment, JPL monitors Moon/Mars
    - JPL's MDNav Section Manager objective: MADCAP processing similar to CARA
    - MADCAP team has participated in CARA User Forums and development of NASA Procedural Requirements on orbital debris and conjunction assessment
    - Covariance matrix attributes for Mars orbiter navigation teams match CARA's
- Work with ESA's Space Situational Awareness program has not explicitly commenced (has been some indirect work through activities of CCSDS Navigation Working Group)
- Significant coordination between JPL Navigation and ESA/ESOC navigation team during the aerobraking period of ESA's ExoMars Trace Gas Orbiter (TGO) mission
    - During this time the frequency of red events at Mars jumped dramatically
        - Before TGO aerobraking, an average of around 7 red events per year
        - During TGO aerobraking end game, one Summary Report had 9 for a single run

# MADCAP - Planned Changes Since 2012

## Improved Workflow Automation

- In 2012, MADCAP was activated by a Linux cron job on a schedule based on the ephemeris update frequency for Lunar and Martian spacecraft
- MADCAP was run daily for Lunar environment, twice weekly for the Mars environment
- In October/November 2014, the Mars run frequency was increased to daily:
  - Larger number of spacecraft operating in the environment (MAVEN and MOM had both arrived within a few days of each other)
  - Characteristics of MAVEN's orbit (eccentric, with periodic deep dips into the Martian atmosphere that constituted a quasi-aerobraking effect)
- JPL MDNav's "TARDIS" workflow automation tool was implemented in October 2014
  - improve the invocation and workflow monitoring functions of MADCAP
  - improvements to error control and logic flow in order to respond to some errors occasionally encountered in the daily operations

# MADCAP - Planned Changes Since 2012

## Work Planned as of 2012, But Incomplete

- Some other previously planned work has not progressed, items remain on "parking lot"
- In 2012 it was thought there might be interest in L1/L2 Lagrange point missions:
  - A parameter file was prepared and tested, but there has been no active interest in monitoring these orbital environments
- CCSDS Conjunction Data Message (CDM), still under development in 2012, has now been used in flight operations for past five years, primarily by United States Air Force:
  - Although principal use of CDM is in Earth's densely populated orbital environment, standard accommodates reporting conjunctions detected in other environments
  - Prototyping of CDM was needed prior to becoming international standard; a simple prototype was built into MADCAP, but an Ops version has not been implemented
  - CDM and MADCAP Summary Report both report conjunction information, but CDM focuses in detail on one predicted conjunction; MADCAP Summary Report provides less information over longer time, covers more predicted conjunctions
  - CDM's detailed focus on single conjunction not one of MADCAP's design points

# MADCAP - Unplanned Accomplishments Since 2012

## Improved Analysis Methods

- Orbit crossing distance calculations are inaccurate during periods of coplanarity between the two bodies
- Refined algorithm was developed to calculate minimum orbit distances when orbits are coplanar or nearly coplanar; has increased run time, but more accurate results
- A check has been inserted to determine when the orbits being compared are coplanar (operationally defined as having angular momentum vectors within an operator specified parameter value)
- For each close approach event, if orbits are determined to be coplanar, the refined algorithm is used to calculate minimum orbit distances and timing which are reported as orbit crossing distances and timing in MADCAP reports
- To avoid long run times for bodies which are often coplanar (e.g. Phobos vs. Deimos), the coplanar algorithm is only used for events within 60 days from the analysis time

# MADCAP - Unplanned Accomplishments Since 2012

## Improved Knowledge of Non-Operational Spacecraft/Objects

- MADCAP team has been interested in how to best include non-operational spacecraft
- Long-term orbital predictions can be produced by propagating previously known states
- Uncertainty is greater than in current solutions, and better than nothing, but because of uncertainties, conjunction events identified with an inactive spacecraft are suspect
- In 2014, MADCAP started including inactive objects in its analysis, and produces the detailed reports and plots, but warnings via the Summary Report are not produced
- NASA's SLS/EM-1 mission will orbit the Moon in the relatively near future
- Engineers at NASA/JSC knew of dead lunar satellites ISRO Chandrayaan-1 and JAXA Ouna, asked JPL whether trajectory knowledge could be improved for EM-1 planning
- In summer 2016, JPL conducted 5 radar tracks using several radio telescopes
  - Chandrayaan-1 successfully located, significantly improving knowledge of the trajectory; orbit plane essentially unchanged, downtrack nearly 180º out of phase
  - JPL did not successfully locate Ouna spacecraft despite several attempts; one "candidate" observation was obtained but could not be confirmed
- Earth-based radar detection of dead lunar satellites was challenging and required reasonably good a priori trajectory (+/- 100 km)

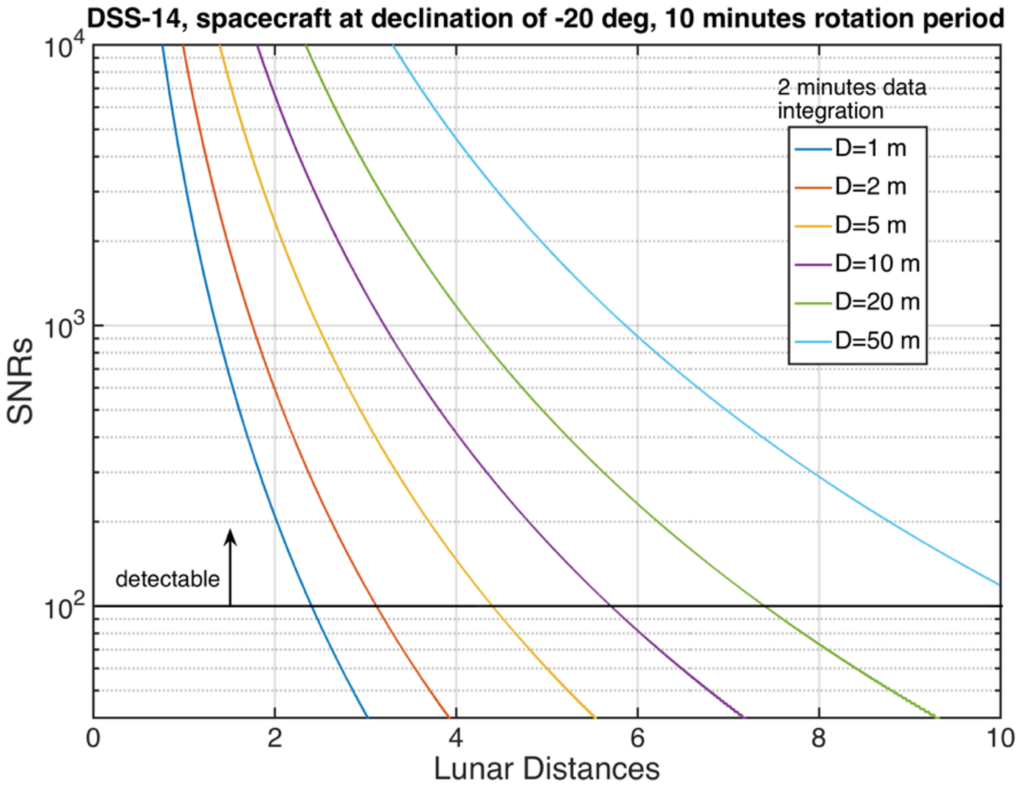
# MADCAP - Unplanned Accomplishments Since 2012

## Dead Lunar Orbiter Radar Observations Summary

| Date | Objective | Transmit | Receive | Results Summary |
|---|---|---|---|---|
| **02-Jul-2016** | (1) Detect calibration satellite<br>(2) Detect Chandrayaan-1 (Doppler) | DSS-14 (X-band) | Green Bank Telescope | (1) Calibrator detected<br>(2) Candidate echo |
| **03-Jul-2016** | (1) Confirm Chandrayaan-1 detection (Doppler, range) | DSS-14 (X-band) | Green Bank Telescope | (1) Chandrayaan-1 confirmed |
| **31-Jul-2016** | (1) Detect Ouna<br>(2) Confirm Chandrayaan-1 | DSS-14 (X-band) | Green Bank Telescope<br>DSS-13 | (1) No Ouna detection<br>(2) Detection, but predicted time was off due to error in orbit determination. |
| **26-Aug-2016** | (1) Detect Ouna<br>(2) Confirm Chandrayaan-1 | Arecibo (S-band) | Green Bank Telescope | (1) Candidate Ouna echo<br>(2) Chandrayaan-1 confirmation |
| **23-Sep-2016** | (1) Detect Ouna<br>(2) Confirm Chandrayaan-1 | DSS-14 (X-band) | Arecibo | (1) Ouna not confirmed<br>(2) Chandrayaan-1 confirmation |

# MADCAP - Unplanned Accomplishments Since 2012

## Radar Detectability of Metallic Sphere at N Lunar Distances



# MADCAP - Unplanned Accomplishments Since 2012

## Improved Reporting

- Since 2012, most improvements in MADCAP reporting appear in the Summary Report
- The Summary Report provides:
  - Information about the bodies included in the analysis (active, inactive, natural body)
  - Information about event thresholds and the method used to establish them
  - Information about ephemeris files and whether they are predicts grade, reference, or something else; and other information such as name, submit date, span
- Summary Report is emailed to wide distribution, essentially constitutes the "Monitor" function providing a "quick look" as to whether or not something requires attention
- If a red event is identified, the "Response" function is activated
- In May 2015, the number of red events identified in a given run was added to the email subject line (zero to *n* events); no longer need to open a report email with 0 red events
- In August 2017, counters for changes compared to the previous run were added: number of ephemeris file updates, number of changed thresholds; changes in blue
- Also in August 2017, MADCAP sends text messages to Ops team to confirm end of run, with a second text message when any red events are identified

# MADCAP - Unplanned Accomplishments Since 2012

## "Renaming the Baby"

- In the beginning (2011), it had been named the "*MArs* Deepspace *Collision Avoidance* Process" (MADCAP)
- Funding for the effort was primarily provided via the Mars Exploration Program
- Mars environment was the first extraterrestrial environment of interest for study with MADCAP
- However, a bit later some funding to support the lunar environment was obtained from the GRAIL mission and NASA/CARA
- Several enhancements were then implemented based on lunar mission requests
- MADCAP acronym was re-purposed to better reflect the large number of applicable missions, the multiple environments, and the functions involved
- Process was re-christened the "*Multimission Automated* Deepspace *Conjunction Assessment* Process"

# MADCAP - A New List of Future Plans

## User Requested Runs

- Typically MADCAP is invoked by automation, but capability to initiate an unscheduled run manually from the Linux command line is preserved for several reasons:
  - Utilized by MADCAP team when new releases are tested, and also when it is necessary to restart process after an error from which recovery is not automated
  - In February 2014, this capability was also used for a special collision avoidance study between NASA's LADEE and LRO missions
- Special study was conducted because MADCAP reports showed that orbit crossing distance between LRO and LADEE would be less than 1 km for a few orbits.
- Use of MADCAP to conduct special analyses helped both projects avoid a potential collision, but required weekend runs by MADCAP team using special ephemeris files
- Inspired idea of allowing flight projects to run "user requested" studies on their own
- Feature would allow users to run studies almost any time without involving MADCAP operations team (with some blackouts during regularly scheduled operations runs)
- High-level concept for this capability has been brainstormed, but not yet implemented

# MADCAP - A New List of Future Plans

## Enhanced Visualization of Orbit Conjunctions

- Current two-dimensional (2D) plots sent out by MADCAP aid in the interpretation of how the spacecraft orbits and timing vary with respect to one another over time
- However, they do not display much information on the geometry of the orbits at the time of the conjunction event
- Much better insight could be gained from a three-dimensional (3D) visualization of the spacecraft orbits at the time of the conjunction
- JPL's Monte navigation software is being enhanced to make generation of 3D orbital representations more seamless and straightforward
- It may be possible for MADCAP to utilize this improvement to generate 3D images of the spacecraft orbits at the time of conjunction and include them as attachments in the emailed reports
- The MADCAP team has been exploring this new capability

# MADCAP - A New List of Future Plans

## Collision Probability (2D and 3D)

- Recent addition of covariance data used by MADCAP for calculating threshold values leads to a natural progression into using the data to calculate collision probabilities
- MADCAP cannot take attitude into account in probability calculations because data sources used by MADCAP do not contain spacecraft attitude information
- $P_c$ calculation is based on a keep-out sphere around each spacecraft or natural body
- MADCAP can calculate 2D collision probabilities based on spherical spacecraft radii and covariance data from OEM files currently used for threshold calculations
- It has been suggested that MADCAP implement NASA/CARA 3D $P_c$ algorithm
- The 3D algorithm does not depend upon some of the simplifying assumptions used in calculating the 2D collision probability
- Calculating and publishing collision probabilities as supplementary information is a future MADCAP goal
- Currently MADCAP team has no plan to use probabilities as main conjunction metric which triggers Response Process

# MADCAP - A New List of Future Plans

## Work with NASA/JSC on SLS/EM-1 and SLS/EM-2 Missions

- The MADCAP team has been discussing with NASA/JSC the use of MADCAP to perform conjunction assessments including the large number of cubesats planned for co-manifest on NASA's SLS/EM-1 and SLS/EM-2
- Current plans call for up to 13 cubesats on SLS/EM-1, up to 40 cubesats on SLS/EM-2
- Options under consideration include:
  - an implementation of the User Requested Run feature in JPL's MADCAP implementation
  - establishing a second instantiation of MADCAP at NASA/JSC
- There could be a near-term implementation of the CCSDS Conjunction Data Message (CDM) in order to support the SLS/EM-1 and SLS/EM-2 missions
- NASA/JSC is familiar with the CDM, and may be interested in receiving CDMs for conjunction events that occur in cis-lunar space during these missions

# Conclusion

- This presentation has provided an update on techniques used at JPL for automated conjunction assessment at Mars and the Moon using the MADCAP software
- Much of the future work that was planned during a previous presentation in 2012 has since been implemented to some degree
- Other unanticipated enhancements have also been applied in order to improve MADCAP's conjunction assessment analysis and reporting
- Some further areas of potential future work to improve current operations have been outlined
- MADCAP provides a "watchdog" infrastructure service at the Moon and Mars, extraterrestrial environments likely to experience an increase in exploration activity by spacefaring nations, where there are already multiple objects in orbit
- With accurate trajectories for future missions regularly made available, MADCAP can provide analyses to help prevent a debris field from being created, benefitting all spacefaring nations wishing to explore these shared orbital environments

# Backup Material

# MADCAP Summary Report Example

From: JPL MDNAV <jplmdnav@airmail.fltops.jpl.nasa.gov>
Date: Monday, March 5, 2018 at 2:56 PM
To: mars_madcap_monitor <mars_madcap_monitor@jpl.nasa.gov>
Subject: MADCAP -- Mars -- Summary -- 1 Red
Analysis Time: 2018-03-05 21:33:54 UTC
Conjunction Assessment Bodies and Types

| | |
|---|---|
| RED Threshold Updates: | 0 |
| ALL Threshold Updates: | 0 |
| Ephemeris Updates: | 5 |

| Body | Name | Type |
|---|---|---|
| 1 | Odyssey | Active |
| 1r | Odyssey | Active/Reference |
| 2 | Mars_Express | Active |
| 2r | Mars_Express | Active/Reference |
| 3 | MRO | Active |
| 4 | MAVEN | Active |
| 5 | MOM | Active |
| 6 | TGO | Active |
| 6r | TGO | Active/Reference |
| 7 | Phobos | Natural |
| 8 | Deimos | Natural |
| 9 | VIKING1 | Inactive |
| 10 | MGS | Inactive |

# MADCAP Summary Report Example (continued)

**Red (Conjunction Data < 'Red' Thresholds and Event < 14 days from Analysis Time)**

| Bodies | OXD value/limit (km) | OXT value/limit (sec) | CAD value/limit (km) | CA Epoch (UTC-SCET) |
|---|---|---|---|---|
| 3-4 | -1.6 5.5 4P | 84.4 254.2 4P | 68.4 ----- -- | 2018-03-16 17:57:50 |

**All (Conjunction Data < 'All' Thresholds for <= 100 days)**

| Bodies | OXD (km) | OXT (sec) | CAD (km) | CA Epoch (UTC-SCET) |
|---|---|---|---|---|
| 3-4 | -10.0 | -1336.7 | 1143.7 | 2018-03-16 08:49:23 |
| 3-4 | -9.1 | 5397.9 | 2719.6 | 2018-03-16 09:46:21 |
| 3-4 | -5.9 | 2741.8 | 1624.3 | 2018-03-16 13:49:28 |
| 3-4 | -1.6 | 84.4 | 68.4 | 2018-03-16 17:57:50 |
| 3-4 | 0.4 | -2562.3 | 2197.2 | 2018-03-16 22:03:50 |
| 3-4 | 3.3 | 4171.1 | 2164.1 | 2018-03-16 22:59:17 |
| 3-4 | 8.1 | 1512.8 | 1093.3 | 2018-03-17 03:05:32 |
| 3-4 | 9.4 | -1142.4 | 981.4 | 2018-03-17 07:13:50 |
| 1-6 | 9.9 | -35.6 | 79.2 | 2018-04-14 14:52:20 |
| 1r-6 | 9.9 | -35.6 | 79.2 | 2018-04-14 14:52:20 |
| 1-6r | 9.9 | -35.6 | 79.2 | 2018-04-14 14:52:20 |
| 1r-6r | 9.9 | -35.6 | 79.2 | 2018-04-14 14:52:20 |
| 1-6 | 9.6 | 7043.4 | 88.1 | 2018-04-27 22:07:50 |
| 1r-6 | 9.6 | 7043.4 | 88.1 | 2018-04-27 22:07:50 |
| 1-6r | 9.6 | 7043.4 | 88.1 | 2018-04-27 22:07:50 |
| 1r-6r | 9.6 | 7043.4 | 88.1 | 2018-04-27 22:07:50 |
| 1-6 | 9.2 | 6997.3 | 97.3 | 2018-05-20 08:07:34 |
| 1r-6 | 9.2 | 6997.3 | 97.3 | 2018-05-20 08:07:34 |
| 1-6r | 9.2 | 6997.3 | 97.3 | 2018-05-20 08:07:34 |
| 1r-6r | 9.2 | 6997.3 | 97.3 | 2018-05-20 08:07:34 |
| 1-6 | 9.8 | 3.6 | 10.7 | 2018-05-20 13:03:03 |
| 1r-6 | 9.8 | 3.6 | 10.7 | 2018-05-20 13:03:03 |

# MADCAP Summary Report Example (continued)

**Notes**

OXD means "Orbit Crossing Distance". OXT means "Orbit Crossing Timing". CAD means "Close Approach Distance".

Data for active spacecraft and natural bodies are displayed in the tables above. Data for inactive spacecraft are not displayed, but they are available in the conjunction metric tables and plots, which have been stored in the output directory listed below. Data for reference trajectories are not considered for Red events, but are considered in the All section for events at least 14 days ahead from the analysis time. Reference trajectories use the same thresholds as the nominal trajectories.

For more information, please see the point of contact listed below.

| | |
|---|---|
| Analysis time: | 2018-03-05 21:33:54 UTC |
| Active spacecraft: | Odyssey, Mars Express, MRO, MAVEN, MOM, TGO |
| Natural bodies: | Phobos, Deimos |
| Inactive spacecraft: | VIKING1, MGS |
| Output directory: | /nav/home/jplmdnav/MADCAP/Mars/archive |
| Point of contact: | MADCAP_Mars@jpl.nasa.gov |
| MADCAP build: | 2.04.0 |

**Red Thresholds -- Polynomial Coefficients**

| Body | Name | OXD0 (km) | OXD1 (km/t) | OXD2 (km/t^2) | OXT0 (sec) | OXT1 (sec/t) | OXT2 (sec/t^2) |
|---|---|---|---|---|---|---|---|
| 1 | Odyssey | 0.0009 | 0.0013 | 0.0000 | 0.0705 | -0.0411 | 0.0096 |
| 2 | Mars_Express | 1.0000 | 0.0000 | 0.0000 | 3000.0000 | 0.0000 | 0.0000 |
| 3 | MRO | 0.0877 | -0.0315 | 0.0040 | 0.0100 | 0.4939 | 0.0765 |
| 4 | MAVEN | 1.3357 | 0.3322 | 0.0042 | 0.0100 | 3.9752 | 1.7560 |
| 5 | MOM | 0.2498 | 0.0014 | 0.0012 | 0.0100 | 33.0089 | 0.3246 |
| 6 | TGO | 1.0000 | 0.0000 | 0.0000 | 3000.0000 | 0.0000 | 0.0000 |
| 7 | Phobos | 30.0000 | 0.0000 | 0.0000 | 15.0000 | 0.0000 | 0.0000 |
| 8 | Deimos | 40.0000 | 0.0000 | 0.0000 | 20.0000 | 0.0000 | 0.0000 |

# MADCAP Summary Report Example (continued)

Red OX Distance Threshold (t) = OXD0 + (OXD1 * t) + (OXD2 * t^2)
Red OX Timing Threshold (t) = OXT0 + (OXT1 * t) + (OXT2 * t^2)
where t = CA Epoch - Ephemeris File Submit Time (in days)

Red thresholds are based on 3-sigma values. Thresholds listed as "P" are based on a quadratic fit of the 3-sigma values as a function of time to the event. The polynomial coefficients used are listed in the table above. Lines for coefficients which have been updated since the last run are colored blue, and each line's body is marked with an "*". Thresholds listed as "C" are based on 3-sigma covariance data provided by the mission.

**All Thresholds -- Constants**

| Body | Name | OXD (km) | CAD (km) |
|---|---|---|---|
| 1 | Odyssey | 10 | 100 |
| 2 | Mars_Express | 10 | 100 |
| 3 | MRO | 10 | 300 |
| 4 | MAVEN | 10 | 3000 |
| 5 | MOM | 20 | 100 |
| 6 | TGO | 10 | 100 |
| 7 | Phobos | 45 | 100 |
| 8 | Deimos | 60 | 200 |

All OX Distance Threshold = OXD
All CA Distance Threshold = CAD

All thresholds are always constants. The constants used are listed in the table above. Lines for constants which have been updated since the last run are colored blue, and each line's body is marked with an "*".

**Ephemerides**

| Body | Ephemeris | Submitted | Begin | End |
|---|---|---|---|---|
| 1 | p_m_od71869-71873_72975_v1.bsp | 2018-02-27 00:05:46 UTC | 25-FEB-2018 21:13:50 UTC | 27-MAY-2018 23:58:50 UTC |
| 1r | p_m_od71869-71873_72975_v1.bsp_V0.1 | Analysis Time | 25-FEB-2018 21:13:50 UTC | 27-MAY-2018 23:58:50 UTC |
| 2* | MOEM_180305OAS_PREDICT__0001.CR.bsp | 2018-03-05 14:00:47 UTC | 22-FEB-2018 12:35:36 UTC | 27-MAR-2018 19:22:41 UTC |
| 2r | MOEM_180122OAS_SCHED____0001.CR.bsp | 2018-01-23 15:52:01 UTC | 21-JAN-2018 01:08:49 UTC | 01-JAN-2022 00:00:00 UTC |
| 3 | pf_psp_rec54351_54346_55121_p-v1.bsp | 2018-03-01 18:11:07 UTC | 01-MAR-2018 03:48:50 UTC | 30-APR-2018 14:07:50 UTC |
| 4* | trj_orb_06667-06670_06831_v1_mvn.bsp | 2018-03-05 19:06:52 UTC | 05-MAR-2018 03:48:50 UTC | 04-APR-2018 16:48:50 UTC |
| 5* | mom_spk_180301-180501_od494_v1_dsn.bsp | 2018-03-05 21:22:58 UTC | 01-MAR-2018 14:30:00 UTC | 01-MAY-2018 12:00:00 UTC |
| 6* | TOEM_180305OAS_PREDICT__0001.CR.bsp | 2018-03-05 11:52:54 UTC | 04-MAR-2018 23:49:28 UTC | 16-JUL-2018 04:46:38 UTC |
| 6r* | TOEM_180302OAS_SCHEDULE_0001.CR.bsp | 2018-03-05 14:55:08 UTC | 26-FEB-2018 08:51:18 UTC | 02-NOV-2019 14:49:42 UTC |
| 7 | mar097.2010-2029.bsp | Analysis Time | 29-DEC-2009 23:58:53 UTC | 01-JAN-2030 23:58:50 UTC |
| 8 | mar097.2010-2029.bsp | Analysis Time | 29-DEC-2009 23:58:53 UTC | 01-JAN-2030 23:58:50 UTC |
| 9 | viking1_nominal_01032017_01032019.bsp | Analysis Time | 28-FEB-2017 23:58:50 UTC | 28-FEB-2019 23:58:50 UTC |
| 10 | p_171030-181030-061214_10yr_nominal.nio | Analysis Time | 30-OCT-2017 05:28:50 UTC | 30-OCT-2018 06:28:50 UTC |

3

Ephemeris files for the bodies analyzed are listed in the table above. Lines for files which have been updated since the last run are colored blue, and each line's body is marked with an "*".

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